

Towards an Imaging Mid-Infrared Heterodyne Spectrometer. T. Hewagama^{1,2}, S. Aslam², H. Jones², T. Kostuk², G. Villanueva^{3,2}, P. Roman², G. B. Shaw², T. Livengood^{1,2}, and J. E. Allen², ¹Dept. Of Astronomy, University of Maryland, College Park, MD 20742, tilak.hewagama@nasa.gov, ²NASA/Goddard Space Flight Center, Greenbelt, MD 20771, ³Physics Dept., Catholic University, Washington, DC 20064.

Introduction: We are developing a concept for a compact, low-mass, low-power, mid-infrared (MIR; 5-12 μm) imaging heterodyne spectrometer that incorporates fiber optic coupling, Quantum Cascade Laser (QCL) local oscillator, photomixer array, and Radio Frequency Software Defined Readout (RFSDR) for spectral analysis. Planetary Decadal Surveys have highlighted the need for miniaturized, robust, low-mass, and minimal power remote sensing technologies for flight missions. The drive for miniaturization of remote sensing spectroscopy and radiometry techniques has been a continuing process. The advent of MIR fibers, and MEMS techniques for producing waveguides has proven to be an important recent advancement for miniaturization of infrared spectrometers. In conjunction with well-established photonics techniques, the miniaturization of spectrometers is transitioning from classic free space optical systems to waveguide/fiber-based structures for light transport and producing interference effects. By their very nature, these new devices are compact and lightweight. Mercury-Cadmium-Teluride (MCT) and Quantum Well Infrared Photodiodes (QWIP) arrays for heterodyne applications are also being developed. Bulky electronics is another barrier that precluded the extension of heterodyne systems into imaging applications, and our RFSDR will address this aspect.

Heterodyne Spectroscopy: In a classical heterodyne system, the telescope beam is mixed with a narrow line width, frequency stabilized, laser to produce a beat frequency which is detected by a detector with sufficient time resolution. The beat, or difference, signal contains the frequency and intensity information of the MIR source. The source spectral region in the vicinity of the laser is down-converted to the radio frequency (RF) region. The high precision analysis of this RF signal has generally involved bulky systems. Multichannel spectrometers have been employed in ground-based investigations of high-precision gas phase molecular ro-vibrational line-shapes at sub-Doppler resolution (1-25 MHz or 0.00003-0.0008 cm^{-1}) to study atmospheric trace gas composition, dynamics, and thermal structure of Venus, Mars, Jupiter, Saturn, Titan, Sun and Earth [1]. Most of these were powered by highly stable, but bulky, gas lasers. Modern Quantum Cascade Laser (QCL) manufacturers offer small footprint and lighter packages for use as the local oscillator (LO).

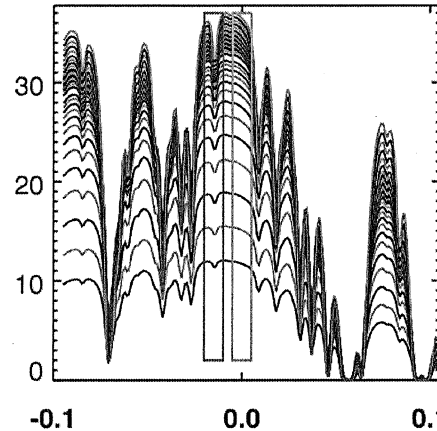


Figure 1: Earth atmosphere in solar occultation (simulated). Each trace corresponds to a different tangent altitude in km. The blue and green boxes represent selected band-passes (width 300 MHz = 0.01 cm^{-1}) that isolate a unique O₃ line and wing region to study the molecular feature as a function of altitude. Although this example shows a $\pm 0.1 \text{ cm}^{-1}$ bandpass, the spectrometer can measure a variable bandpass or simply narrow spectral regions of interest.

Towards an Imaging System: Heterodyne imaging system have been anticipated for some time [2]. An advantage of the heterodyne technique is the ability to probe frequency bands in the limit of the Doppler broadened line width or LO line width. Such a device can select a specific ro-vibrational transition from a single molecular species (Fig. 1), free of contamination from other species, for rapid imaging of a scene in a narrow band. In an operational mode in which data rate is constrained by telemetry, a nadir-looking spacecraft telescope can sample a broad swath in a narrow frequency band to identify spatial irregularities; the sensor's ReadOut Integrated Circuit (ROIC) can be used to interrogate pixel groups and the Digital Signal Processor (DSP) will filter the appropriate frequency range corresponding to the software-defined narrow band. In another mode, the system can scan the spectral line region by tuning the operating frequency of the QCL local oscillator. The operational wavelengths in the 5-12 μm range permit observing the thermal radiation of target sources for source characterization

in daylight and at night. The RFSDR can also be used in frequencies extending to the FIR/sub-mm regions.

Sampling the Image: Low attenuation MIR optical fibers (Silver-Halide and Chalcogenide) and couplers are now commercially available. In our design, the telescope field of view (FOV) is delivered to a bundle of MIR fibers (Fig. 2). Each fiber samples a diffraction limited spatial region of the telescope FOV. The QCL signal is also sampled by a bundle of MIR fibers. The individual fibers are combined using fiber couplers. A third bundle of fibers carries the combined signals. The latter fiber bundle couples to the photomixer (MCT or QWIP) pixels either via a lenslet array or an ensemble of tapered waveguides arranged to directly illuminate the photomixer pixels. The signals from the photomixer pixels are processed by the RFSDR.

Processing the RF response: A number of techniques have been developed for the analysis of the RF difference signals generated the photomixer. For example, an bank of analog filter were used in our heterodyne spectrometers [1]. Other techniques include Acousto Optical Spectrometer (AOS) [3], autocorrelator, and Chip Transform Spectrometer (CTS) [4]. We employ a Fast Fourier Transform based approach.

RFSDR Operational Principle: The function of the Radio Frequency Software-Defined Readout (RFSDR) is to process and present, in real time, the set of absorption spectra from the photomixer pixel array (Fig. 2). The heterodyned response results in frequency bandpasses in the GHz regime. Controlled by an onboard high-speed microcontroller, the amplified times-series voltages of the user-selected pixels are

multiplexed by the FPA to a 4GSPS ADC — after anti-alias filtering and post amplification. The 12-bit digital samples are queued into a high-speed FIFO memory buffer, retrieved by the micro-controller, and routed by it in packets via a standard communications (firewire/USB) interface to a remote computer, along with header and housekeeping data. The application-specific software restores the packets into continuous time-series streams for each selected pixel and digitally transforms these streams into the frequency domain. After windowing, the results are routed to a number of multi-tapped FIR bandpass filters in which the center and bandwidth frequencies can be selected in order to view specific regions of the frequency or wavelength spectra. The incoming packets are also stored to file for playback of the data.

Applications: As shown in Fig. 1, the spectrometer can be used in narrow band imaging applications where telemetry is limited but the science calls for continuous monitoring of spectral lines. Since the time series data stream from the array pixel is digitally processed, in cases where telemetry is not constrained, the full pixel-by-pixel spectrum within the bandpass can be returned. The thermal background is removed by chopping at low rates (~5 Hz) between source and background using a mechanical chopper or shutter. ROIC integrated photomixer arrays will permit addressing of individual or groups of pixels.

References: [1] Kostiuk T. (1994) *IR. Phys. Tech.*, 35, 243. [2] Hutchinson, D. P., Richards, R. L., Simpson, M. L. (1998) *OSTI*, 1998-03-01. [3] Sonnabend G. *et al.* (2005) *A&A*, 435, 1181. [4] Villanueva G. L. *et al.* (2006) *IEEE*, 54, 1415-1424.

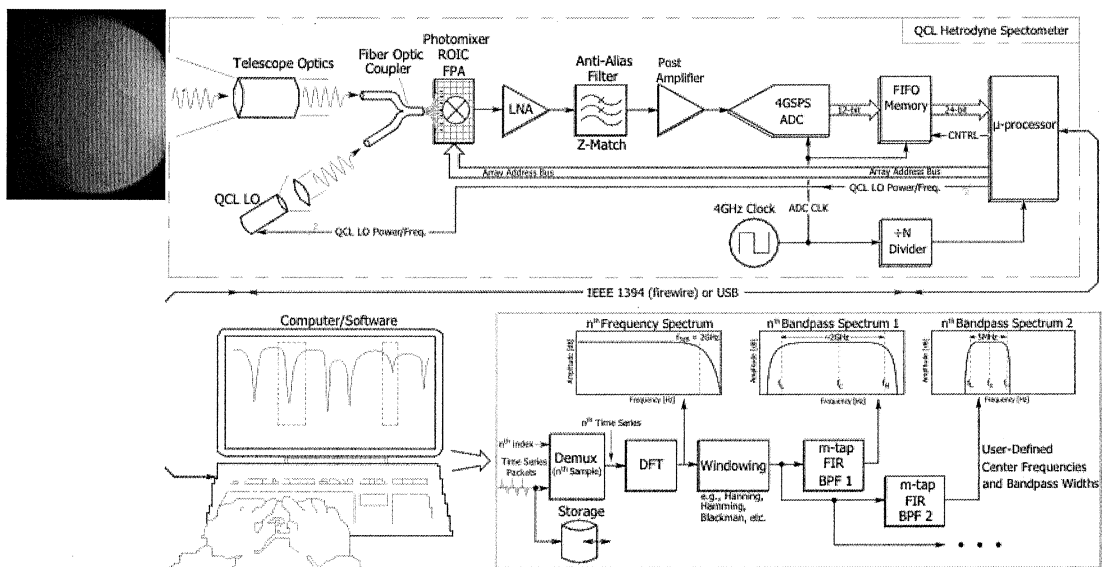


Figure 2: Functional block diagram of the spectrometer components. The telescope and QCL signals are sampled by fibers, combined and presented to the photomixer pixels. Difference signals are de-multiplexed, transformed to the frequency domain, windowed, and filtered at spectral regions of interest.